Selective Use of Stainless Reinforcement Major Road Bridge

Contents

Abstract

Major structures including bridges provide many benefits to established modern, developing and expanding societies. These benefits include the straightforward mass movement of people and goods, the development and growth of regional and national economies including providing appropriate levels of connectivity between manufacturing sites, distribution sites and points of sale.

If we are to continue to develop as a society, accommodate the growing global urban population and keep both people and assets safe, it is critical that we rethink our approach to appropriate materials selection for structures which should be aligned to having a deeper understanding of material degradation mechanisms. Changing our alignment when it comes to building structures does not mean we have to spend more money to achieve the required outcomes. It just means we have to become better educated to understand all the expected material degradation issues and therefore design structures with the appropriate use of resilient materials to have structurally safe and reliable operational lives >120 years.

Unfortunately, and across the world we have a legacy of bridges built during the 1950s, 1960s and 1970s where speed of construction and use of easily available materials was the norm. A significant driver was to provide good connectivity between urban centers in order to facilitate the support for economic growth within and between different countries in the world. These bridges, as they were generally built with the available materials at the time following traditional bridge designs resulted in masses of functional bridges that were all susceptible to degradation from both corrosion of structural steel components and fatigue failures resulting from the increasing traffic levels and increased vehicle weights seen in recent decades.

Interestingly, some forward-thinking organizations have in recent decades built (or rebuilt) bridges with different materials selection thinking aligned to understanding likely future materials failures. The result of this approach is based around the concept of selective adoption of appropriate stainless steels in areas of bridge structures where corrosion and/or fatigue failures are highly likely. The duplex family of stainless steels are well-suited to this type of materials adoption, because they combine high strength with good corrosion resistance and good formability whilst remaining ductile down to -40°C.

Introduction

The global building and infrastructure sector is a major consumer of steel products with around 900 million tonnes being consumed annually. This figure represents around 50% of the total annual global steel consumption. Furthermore around 325 million tonnes are reinforcing bar products which is around 36% of the annual global steel consumption.
Stainless steels represent a very small proportion of this total consumption with around 1%, or 9 million tonnes of stainless steels being consumed annually in this sector. [1] The use of stainless steels for structural products is much lower. However, in our present times the need to consider and use stainless steels is becoming much more compelling for the following reasons.

a. Many structures built during the 1950s, 1960s and 1970s, particularly bridges, are now being declared as structurally deficient.
b. Both fatigue and corrosion are the major contributing factors resulting in structural deficiency.
c. The corrosion of reinforcing bar products remains hidden for many years before becoming visible after which repairs become both difficult and costly.
d. More than 60% of repairs to corroded reinforcement fail within 10 years of repair completion. [2]
e. Structures built in marine environments and in regions of our world where de-icing salts are used suffer from Chloride-induced pitting corrosion which can be completely avoided through different materials thinking. This corrosion mechanism often results in structural failures which create major economic damage and sadly, sometimes the loss of life.

Stainless steels despite all their strong attributes for use in the built environment, are frequently discounted from materials selection processes due to their high cost and a lack of understanding of the key properties of the available grades of stainless steels. Fortunately, the tide is beginning to turn, and some enlightened bridge designers are now beginning to consider and use stainless steels as a key construction material particularly where corrosion is likely to occur and/or in hard to access locations when considering future maintenance needs. These designers tend to adopt the concept of the selective use of stainless steel, particularly for large structures which provides both an economic project / life cycle cost and structural longevity.
It is this concept that will primarily be discussed in this case study.

Discussion

A large highway bridge built in the north of the UK in the early 1960s was dogged with ongoing maintenance problems throughout its operating life. It was eventually replaced with a new bridge which was opened in 2017.

The original bridge was built primarily with concrete and structural steel reinforcement and as a result of operating in a marine environment where de-icing salts were employed during the winter months, the bridge suffered from corrosion of the reinforcing materials. These ongoing corrosion problems created a maintenance nightmare which impacted both directly and indirectly on the traffic flow across the bridge, which was averaging around 24 million vehicles per annum during its later years of operation.

The primary significant corrosion problem was Chloride (or pitting) corrosion of the Carbon Steel reinforcing materials. General atmospheric corrosion was also present, however the rate of progress of the pitting corrosion was much higher due to the high concentration of Chloride ions. Both the ever-present marine environment and the use of de-icing salts contributed directly to the corrosion problem. Carbon steel is not able to withstand both pitting corrosion and atmospheric corrosion.

It is fair to state that during the design and building period of the original bridge, the impact of Chloride ions and their diffusion through concrete, whether present in the local atmosphere (i.e.; marine locations) or added via the use of products like de-icing salts was not fully understood across the building and infrastructure sector, particularly as the concrete after pouring and curing naturally created a corrosion-resistant alkaline environment. [3]

It is fair to say that the problem of Chloride corrosion within reinforced concrete structures is better understood in current times however, some important associated organizational behaviors within the building and infrastructure industrial sector are still dominant and suppress or prevent the selection of stainless steels. These features include;

a. Maintenance of structures is seen as lucrative business because it employs many people and is a profitable undertaking. Interestingly 20% of reinforced concrete repairs fail after just 5 years and as we already know >60% of repairs fail again within 10 years of the repair completion, leaving a material degradation legacy which can result in catastrophic or partially catastrophic structural failures. [4] Hence it can be firmly argued that the need for regular maintenance of structures is not an effective use of both available cash and resources before even considering the massive disruptive and local air pollution effects that come with closing traffic routes whilst undertaking repairs.

b. Whilst it is understood that stainless steel reinforcement will not corrode when the appropriate grade for the environment is selected, the high cost of stainless steels prevents the stainless steel choice being routinely made. If expected corrosion mechanisms can be understood and corrosion locations defined during the structural design process, then the selective use of stainless steel can be adopted which offers an economic solution rather than considering a total adoption of stainless steel.

c. Galvanized reinforcement materials are considered a suitable alternative that will not corrode in the presence of mechanisms causing both general corrosion and to some degree, pitting corrosion. What is sadly often overlooked is that protective coatings all eventually fail and many of the failures result from installation handling damage, storage damage, on-site handling damage and/or poor handling during product receipt at installation sites. These issues represent direct damage to the Zinc coating and therefore make the substrate steel products susceptible to corrosion. However, what is often not fully understood is that Zinc coatings also offer protection against galvanic corrosion where the Zinc acts as a sacrificial anode in the protection process. The presence of Chloride ions coupled with pore water in concrete means that the salty water provides better conductivity and the zinc cathodically protecting the substrate steel is consumed at a faster rate, thus decreasing the overall lifetime of the coating and exposing the steel to corrosive media. [5]

d. It is also important to note that the availability of high strength duplex stainless steels is not fully recognized nor understood within the building and infrastructure community. These grades not only provide the level of corrosion protection needed they also offer the opportunity to reduce the amount of concrete cover needed and thereby rebalance the overall materials cost.

e. Sadly, the notion of the 'selective use concept' for stainless steels is not yet widely recognized and adopted but has been described below to aid understanding.

The Selective Use of Stainless Steels

The selective use of stainless steel reinforcement is a concept where around 10% of, for example, the total reinforcing bar products are replaced with stainless steel reinforcement, generally in the first sub-surface layers of reinforcement in the concrete. This approach delivers four significant benefits, namely;

a. The total cost of the reinforcement only increases by a modest amount, representing around 3-4% of the total cost of a structure.
b. The amount of concrete needed can be reduced as a result of the high strength benefit offered by duplex stainless steels particularly, thereby mitigating the materials cost increase when selecting stainless steels.
c. The total materials cost is typically somewhere between 15% and 25% of the total cost of creating a structure, meaning its overall impact is not the most significant element of a project.
d. Applying duplex stainless steel reinforcement in the first sub-surface layers is appropriate as the diffusion of both CO2 and Chloride ions does not reach the deeper layers of steel reinforcement with both features needed to initiate corrosion of the reinforcement. [6]

Whilst the use of stainless steels in the construction sector remains low at around 1% of the total steel products used annually in this sector, there is an opportunity to build with structural longevity in mind by selectively using stainless steels. Furthermore, if the global population living in urban settings is expected to increase from 57% of the total population to 70% of the total population by 2050, then it becomes essential that we build with structural resilience and service longevity as core structural imperatives.

Adopting this approach will also offer a 'simple-to-execute' societal decarbonization mechanism as today 22% of the global steel industry GHG production emissions result from a need to replace corroded steels. These emissions can be avoided through the use of resilient and non-corrosive materials like stainless steels.

The following charts will provide an overview of the benefits of employing a selective use of duplex stainless steel reinforcement in this case. [7]

Life Cycle Costs

Chart 1 *Life Cycle Cost for the as-Built Bridge; 11% Duplex Stainless Steel Rebar for the Deck*

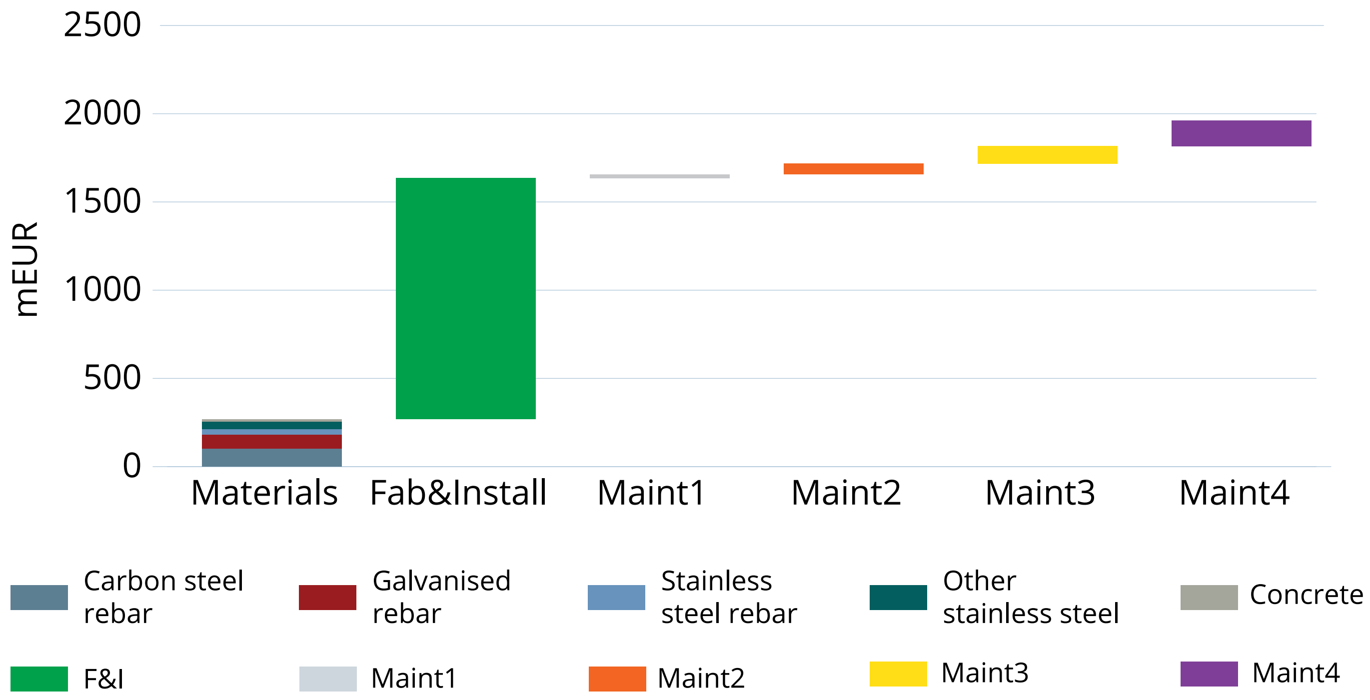
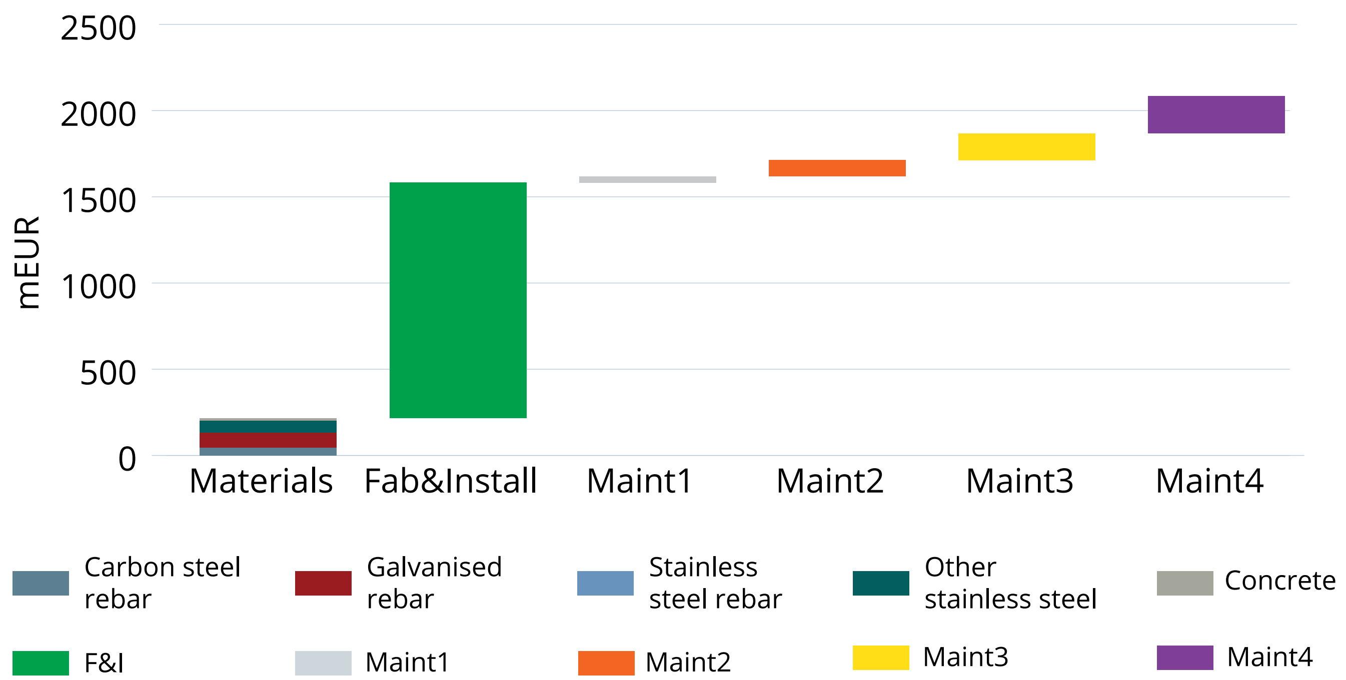


Chart 2 *Life Cycle Cost for the Bridge with no Stainless Steel Reinforcement*



Key to the terms used in the above charts.

a. **Materials**; this is the total cost of all materials used in the construction of the bridge.
b. **Fab&Install**; this is the total cost of the fabrication, treatment and installation of all the materials used in the construction of the bridge.
c. **Maint1**; This is the expected cost of major maintenance after 25 years of operation.
d. **Maint2**; This is the expected cost of major maintenance after 50 years of operation.
e. **Maint3**; This is the expected cost of major maintenance after 75 years of operation.
f. **Maint4**; This is the expected cost of major maintenance after 100 years of operation.

Minor maintenance costs have not been considered nor studied in this work as they are lower cost elements that do not present significant variations related to different material choices.

The interesting and salient observations from undertaking these life cycle cost assessments when considering different material choices are shown in Table 1 below.

Table 1 *Summary of Life Cycle Cost Differences when Considering Different Materials Choices*

Feature	As Built Bridge	Traditional Bridge	Comments
Cost to Build	1640m EUR	1585m EUR	+3.5% for stainless
Cost to Maintain	325m EUR	500m EUR	-35.0% for stainless
Life Cycle Cost	1965m EUR	2085m EUR	-5.8% for stainless
Materials Cost	270m EUR	215m EUR	+25.6% for stainless
Fab&Install Cost	1370m EUR	1370m EUR	
Material Cost %	13.7%	10.3%	Low % of the total cost
Fab&Install Cost %	69.8%	65.7%	Manpower intensive
Maint Cost %	16.5%	24.0%	Manpower intensive

The as-built bridge contains 11% stainless steel reinforcement including couplers and fixings across the bridge deck. By contrast, the traditional bridge alternative contains no stainless steel reinforcement and no associated stainless steel products.

The fabrication and installation costs are essentially the same for both bridges as a result of two cost-balancing factors, namely;

a. The cost of fabricating stainless steels is generally a little higher than that for traditional structural steels, although only modest additional fabrication was needed for this project.

b. The amount of concrete needed can be reduced when employing stainless steel reinforcement and therefore there is less concrete to pour thereby reducing the material and pouring costs.

The cost to maintain has been assessed over 100 years of operation with a prudent perspective of the expected level of needed maintenance when stainless steels have not been employed. This assessment approach was adopted to not be overly favorable towards stainless steels.

The important learnings when considering different materials mixes, in large structures are as follows.

a. The cost of materials is relatively low compared to the building and installation costs and even the future major maintenance costs.

b. The small additional cost of using a proportion of resilient materials (ie; 55m EUR in this case) provides a reduction in future maintenance costs by at least 3 times the additional cost of those resilient materials (ie; 175m EUR in this case).

Key observations and guidance arising from this assessment work include;

a. The cost of materials is not a 'big ticket' element within the total cost of building a large structure and therefore cannot logically be argued as a sensible consideration for reducing up-front costs by selecting lower cost materials.

    1. This observation takes on an even greater significance when the future cost of maintenance is considered when non-resilient materials have been employed.

b. The opportunities to reduce future operational disruption and deliver significant maintenance cost savings arise directly from the smart selective use of resilient materials.

    1. Adopting the selective use of resilient materials also will avoid any future monetization attached to emissions associated with the usage phase of structures, particularly during avoidable maintenance periods.

It is also important to note that because major maintenance is expensive and corrosion problems in reinforced structures are not always visible, the major maintenance tasks are often delayed or deferred which only increases both major maintenance and corrosion repair costs when the major maintenance is actually approved and undertaken. This is clearly a false economy but is a recognized reflection of reality. This 'short termist' approach only serves to reinforce the benefits of the selective use of stainless steels in structures.

Whilst life cycle cost assessments are highly valuable when considering material selection requirements for large structures it is also highly valuable to consider emissions over the operating life of large structures. The next section of this study will examine the life-cycle emissions profile associated with this bridge.

Life-Cycle Emissions

Today there is much focus and attention on reducing the production emissions associated with many materials including those used extensively in the building and infrastructure sector. The materials that are being heavily scrutinized and directed to progressively reduce their cradle-to-gate production emissions include steels, cement & concrete and Aluminium.

In the same manner as the life-cycle cost analysis was undertaken for this bridge a life-cycle emissions assessment has been undertaken and has been applied to the same 7 elements, namely materials production, materials fabrication, building and installation work and 4 major maintenance requirements. [7]

Chart 3 *Life Cycle Emissions for the as-Built Bridge; 11% Duplex Stainless Steel Rebar for the Deck*

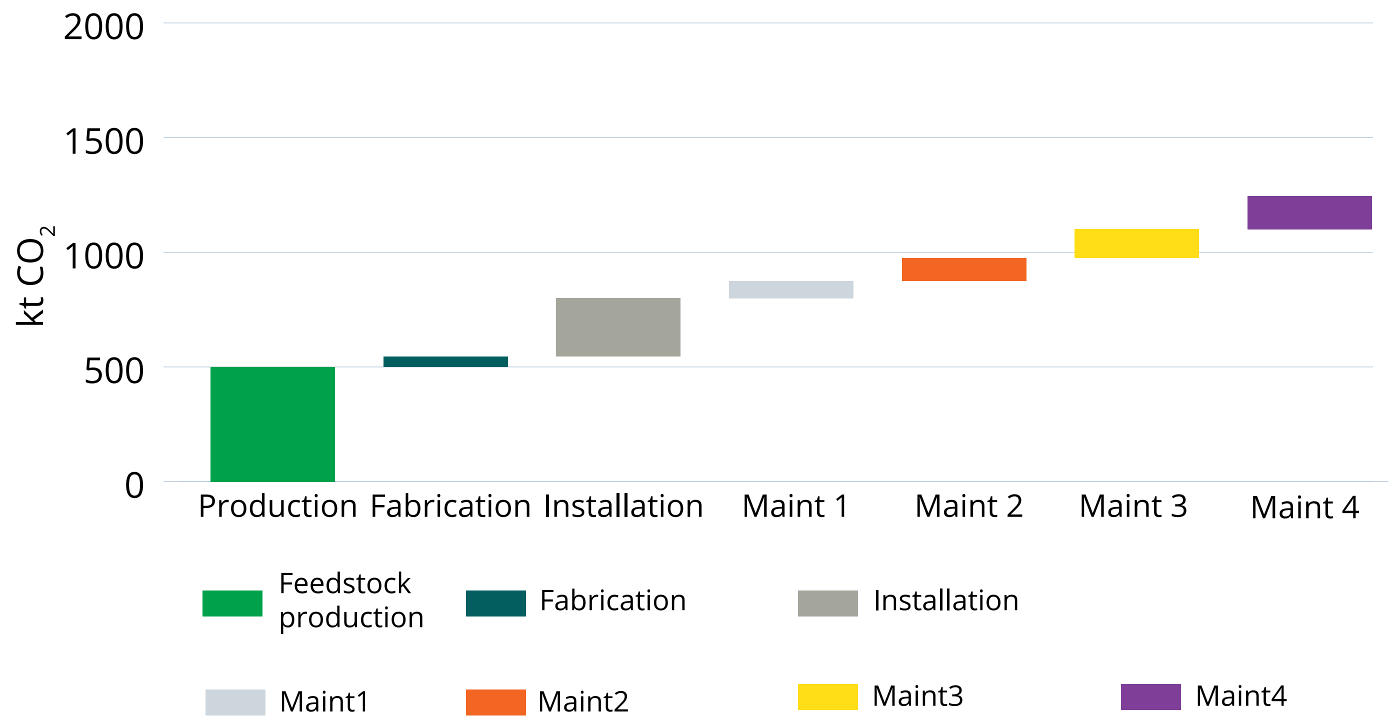
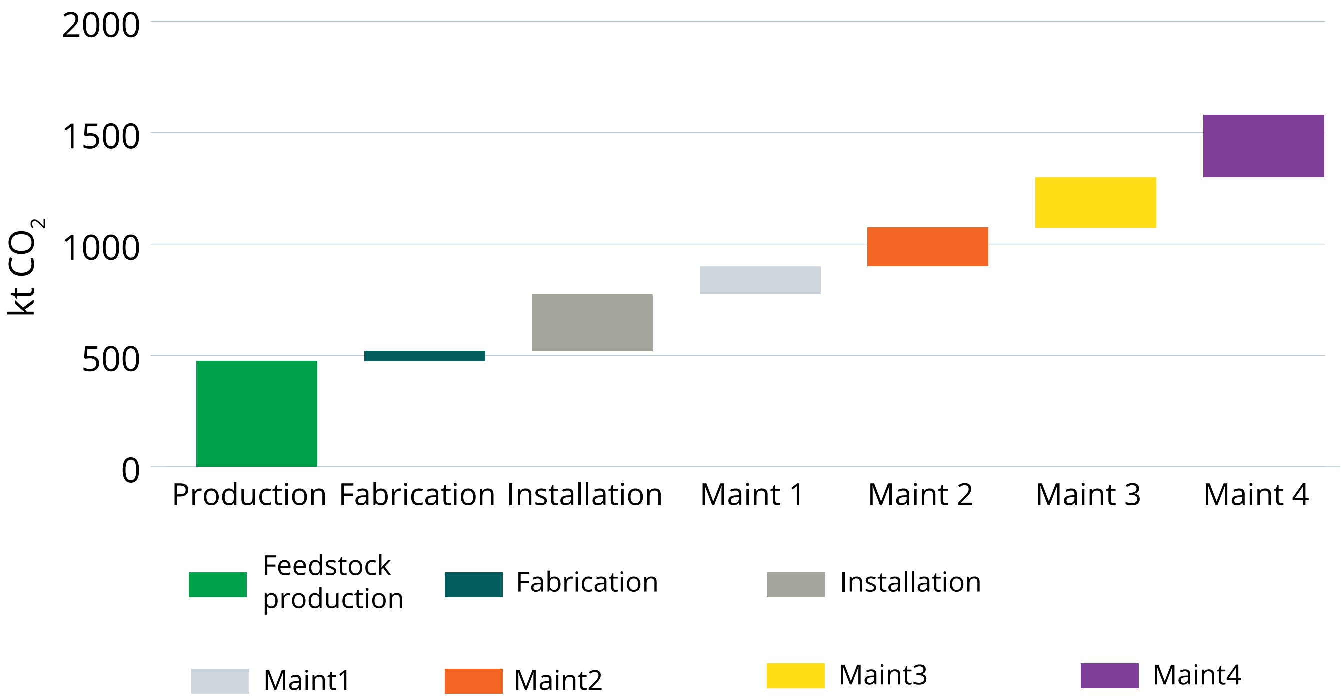


Chart 4 *Life Cycle Emissions for the Bridge with no Stainless Steel Reinforcement*



In this assessment the total material production emissions have been combined into a single figure and the following observations are noteworthy.

a. The total material cradle to gate production emissions were 500kt of CO2e (as built) and 475kt of CO2e (with no stainless steel rebar products)
b. The total emissions associated with the installation tasks were 255kt of CO2e for both cases.
c. The cumulative emissions associated with major maintenance tasks were 445kt of CO2e (as built) and 805kt of CO2e (with no stainless steel rebar products)

The important features to therefore note are;

- The 'big ticket' items affecting the life cycle emissions profile of a large structure are;
  - Total major maintenance emissions, representing around 50% of the total life cycle emissions of the project.
  - Material production emissions, representing around 30% of the total life cycle emissions of the project.
- Selectively using appropriate stainless steel products increases the materials production emissions by (in this case) 25kt of CO2e which is an increase of just 5%.
- Selectively using appropriate stainless steel products decreases the materials maintenance emissions by (in this case) a massive 360kt of CO2e which is a decrease of 45%. This reduction more than offsets the modest increase in overall material production emissions by some 14 fold.

The major arguments when considering life cycle emissions is to firstly understand what tasks and/or activities are actually 'emissions creating' in a significant manner. This study has shown that 2 activities influence around 80% of the total life-cycle emissions, namely major maintenance and materials production.

Secondly an understanding of how materials choices have a direct and significant impact on future emissions is vital in order to make the most appropriate materials choices. This study has shown that by selecting more resilient materials in a selective manner may increase the materials production emissions by around 5% but this then facilitates a massive (45%) reduction in the emissions associated with major maintenance tasks.

Conclusions

When considering building major structures, the choice of materials used has a major impact on the life cycle costs and emissions associated with those structures particularly during the operational phase of structures. The use of reinforced concrete in structures may be a well-established approach, however in regions where corrosion of traditional structural steels is highly likely, the onset and progress of corrosion is hidden for many years which makes the true understanding of structural integrity difficult.

The notion of selective use of resilient materials is a game-changer for structures because it overcomes the hidden material degradation issues described above and offers the following clear benefits.

a. The notion of considering the selective use of resilient materials concept is simple and straightforward and enhances the approach by which structures can be designed within operational longevity as a primary objective.
b. Undertaking material life-cycle assessments for both costs and emissions provides clear guidance for the selective use of resilient materials like stainless steels in order to build economical, low maintenance and safe structures with service lives in excess of 120 years.
c. A small increase in up-front materials costs resulting from the selection of more resilient materials like stainless steels delivers significant cost reductions in the operational or usage phase of the structure thereby fully justifying the selection of resilient stainless steel products.
d. The use of stainless steels in this case delivers a massive reduction in emissions during the operational phase of the structure which is much more than industry production emissions reduction programs can currently deliver.

Whilst this case study is based on one specific structure there are now many other large structures around the world that have adopted the same philosophy and are seeing similar or greater benefits. Detrimental corrosion in structures is truly avoidable and just requires different thinking. As mass urbanization continues, the time is here where we must consider the benefits of selectively using resilient materials. Duplex stainless steels are a key family of materials that are game changers for the built environment. We should not leave poor outcomes resulting from weak materials selection to chance. We must protect our people and our society by making strong and appropriate material selection decisions.

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